RADIOACTIVITY

Pleiochroic haloes

v

JOLY

OF·GEMS·&c
GEM·CUTTING
GEMSTONES·OF·NORTH·AMERICA·PROSPECTING·FOR·GEM
STONES·AND
MINERALS
MINERALOGY·EMERALD·AND·OTHER·BERYLS·CATALOG
EX
LIB-
RIS
JOHN
SIN
KAN
KAS

Cat

PLEOCHROIC HALOES

BY

J. JOLY, F. R. S.

FROM THE SMITHSONIAN REPORT FOR 1914, PAGES 313–327
(WITH 3 PLATES)



(PUBLICATION 2333)

WASHINGTON
GOVERNMENT PRINTING OFFICE
1915

RTL 013540

PLEOCHROIC HALOES

BY

J. JOLY, F. R. S.

FROM THE SMITHSONIAN REPORT FOR 1914, PAGES 313-327
(WITH 3 PLATES)



(PUBLICATION 2333)

WASHINGTON
GOVERNMENT PRINTING OFFICE
1915

PLEOCHROIC HALOES.[1]

By J. Joly, F. R. S.

[With 3 plates.]

It is now well established that a helium atom is expelled from certain of the radioactive elements at the moment of transformation. The helium atom or alpha ray leaves the transforming atom with a velocity which varies in the different radioactive elements, but which is always very great, attaining as much as 2×10^9 centimeters per second, a velocity which, if unchecked, would carry the atom round the earth in less than two seconds. The alpha ray carries a positive charge of double the ionic amount.

When an alpha ray is discharged from the transforming element into a gaseous medium its velocity is rapidly checked and its energy absorbed. A certain amount of energy is thus transferred from the transforming atom to the gas. We recognize this energy in the gas by the altered properties of the latter; chiefly by the fact that it becomes a conductor of electricity. The mechanism by which this change is effected is in part known. The atoms of the gas, which appear to be freely penetrated by the alpha ray, are so far dismembered as to yield charged electrons or ions, the atoms remaining charged with an equal and opposite charge. Such a medium of free electric charges becomes a conductor of electricity by convection when an electromotive force is applied. The gas also acquires other properties in virtue of its ionization. Under certain conditions it may acquire chemical activity and new combinations may be formed or existing ones broken up. When its initial velocity is expended the helium atom gives up its properties as an alpha ray and thenceforth remains possessed of the ordinary varying velocity of thermal agitation. Bragg and Kleeman and others have investigated the career of the alpha ray when its path or range lies in a gas at ordinary or obtainable conditions of pressure and temperature. We will review some of the facts ascertained.

[1] Being the Huxley lecture, delivered at the University of Birmingham on Oct. 30, 1912. Reprinted by permission. Published in Bedrock, London, January, 1913.

The range or distance traversed in a gas at ordinary pressures is a few centimeters. The following table, compiled by Geiger, gives the range in air at the temperature of 15° C.:

	Centimeters.		Centimeters.
Uranium 1	2.50	Thorium X	4.30
Uranium 2	2.90	Th emanation	5.00
Ionium	3.00	Thorium A	5.70
Radium	3.30	Thorium C_1	4.80
Ra emanation	4.16	Thorium C_2	8.60
Radium A	4.75	Radioactinium	4.60
Radium C	6.94	Actinium X	4.40
Radium F	3.77	Act emanation	5.70
Thorium	2.72	Actinium A	6.50
Radiothorium	3.87	Actinium C	5.40

It will be seen that the ray of greatest range is that proceeding from thorium C_2, which reaches a distance of 8.6 centimeters. In the uranium family the fastest ray is that of radium C. It attains 6.94 centimeters. There is thus an appreciable difference between the ultimate distances traversed by the most energetic rays of the two families. The shortest ranges are those of uranium 1 and 2.

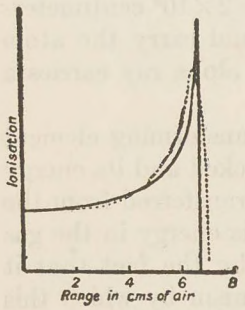


FIG. 1.

The ionization effected by these rays is by no means uniform along the path of the ray. By examining the conductivity of the gas at different points along the path of the ray the ionization at these points may be determined. At the limits of the range the ionization ceases. In this manner the range is, in fact, determined. The dotted curve (fig. 1) depicts the recent investigation of the ionization effected by a sheaf of parallel rays of radium C in air, as determined by Geiger. The range is laid out horizontally in centimeters. The numbers of ions are laid out vertically. The remarkable nature of the results will be at once apparent. We should have expected that the ray at the beginning of its path, when its velocity and kinetic energy were greatest, would have been more effective than toward the end of its range when its energy had almost run out. But the curve shows that it is just the other way. The lagging ray, about to resign its ionizing properties, becomes a much more efficient ionizer than it was at first. The maximum efficiency is, however, in the case of a bundle of parallel rays, not quite at the end of the range, but about half a centimeter from it. The increase to the maximum is rapid, the fall from the maximum to nothing is much more rapid.

It can be shown that the ionization effected anywhere along the path of the ray is inversely proportional to the velocity of the ray at that point. But this evidently does not apply to the last 5 or 10

millimeters of the range where the rate of ionization and of the speed of the ray change most rapidly. To what are the changing properties of the rays near the end of their path to be ascribed? It is only recently that this matter has been elucidated.

When the alpha ray has sufficiently slowed down, its power of passing right through atoms, without appreciably experiencing any effects from them, diminishes. The opposing atoms begin to exert an influence on the path of the ray, deflecting it a little. The heavier atoms will deflect it most. This effect has been very successfully investigated by Geiger. It is known as "scattering." The angle of scattering increases rapidly with the decrease of velocity. Now the effect of the scattering will be to cause some of the rays to complete their ranges or, more accurately, to leave their direct line of advance a little sooner than others. In the beautiful experiments of C. T. R. Wilson we are enabled to obtain ocular demonstration of the scattering. The photograph (fig. 2), which I owe to the kindness of Mr. Wilson, shows the deflection of the ray toward the end of its path. In this case the path of the ray has been rendered visible by the condensation of water particles under the influence of the ionization; the atmosphere in which the ray travels being in a state of supersaturation with water vapor at the instant of the passage of the ray. It is evident that if we were observing the ionization along a sheaf of parallel rays, all starting with equal velocity, the effect of the bending of some of the rays near the end of their range must be to cause a decrease in the aggregate ionization near the very end of the ultimate range. For, in fact, some of the rays complete their work of ionizing at points in the gas before the end is reached. This is the cause, or at least an important contributory cause, of the decline in the ionization near the end of the range, when the effects of a bundle of rays are being observed. The explanation does not suggest that the ionizing power of any one ray is actually diminished before it finally ceases to be an alpha ray.

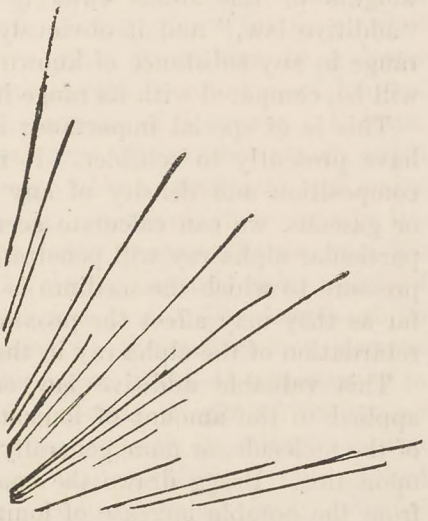


FIG. 2.

The full line in figure 1 gives the ionization curve which it may be expected would be struck out by a single alpha ray. In it the ionization goes on increasing till it abruptly ceases altogether, with the entire loss of the initial kinetic energy of the particle.

A highly remarkable fact was found out by Bragg. The effect of the atom traversed by the ray to check the velocity of the ray is independent of the physical and chemical condition of the atom. He measured the "stopping power" of a medium by the distance the ray can penetrate into it compared with the distance to which it can penetrate in air. The less the ratio the greater the stopping power. The stopping power of a substance is proportional to the square root of its atomic weight. The stopping power of an atom is not altered if it is in chemical union with another atom. The atomic weight is the one quality of importance. The physical state, whether the element is in the solid, liquid, or gaseous state, is unimportant. And when we deal with molecules the stopping power is simply proportional to the sum of the square roots of the atomic weights of the atoms entering into the molecule. This is the "additive law," and it obviously enables us to calculate what the range in any substance of known chemical composition and density will be, compared with its range in air.

This is of special importance in connection with phenomena we have presently to consider. It means that, knowing the chemical composition and density of any medium whatsoever, solid, liquid, or gaseous, we can calculate accurately the distance to which any particular alpha ray will penetrate. Nor have the temperature and pressure to which the medium is subjected any influence save in so far as they may affect the proximity of one atom to another. The retardation of the alpha ray in the atom is not affected.

This valuable additive law can not, however, in strictness be applied to the amount of ionization attending the ray. The form of the molecule, or more generally its volume, may have an influence upon this. Bragg draws the conclusion, from this fact as well as from the notable increase of ionization with loss of speed, that the ionization is dependent upon the time the ray spends in the molecule. The energy of the ray is, indeed, found to be less efficient in producing ionization in the smaller atoms.

Before leaving our review of the general laws governing the passage of alpha rays through matter, a point of interest must be referred to. We have hitherto spoken in general terms of the fact that ionization attends the passage of the ray. We have said nothing as to the nature of the ionization so produced. But in point of fact the ionization due to an alpha ray is sui generis. A glance at one of Wilson's photographs (fig. 2) illustrates this. The white streak of water particles marks the path of the ray. The ions produced are evidently closely crowded along the track of the ray. They have been called into existence in a very minute instant of time. Now we know that ions of opposite sign if left to themselves recombine. The rate of recombination depends upon the

product of the number of each sign present in unit volume. Here the numbers are very great and the volume very small. The ionic density is therefore high, and recombination very rapidly removes the ions after they are formed. We see here a peculiarity of the ionization effected by alpha rays. It is linear in distribution and very local. Much of the ionization in gases is again undone by recombination before diffusion leads to the separation of the ions. This "initial recombination" is greatest toward the end of the path of the ray where the ionization is a maximum. Here it may be so effective that the form of the curve is completely lost unless a very large electromotive force is used to separate the ions when the ionization is being investigated.

We have now reviewed recent work at sufficient length to understand something of the nature of the most important advance ever made in our knowledge of the atom. Let us glance briefly at what we have learned. The radioactive atom in sinking to a lower atomic weight casts out with enormous velocity an atom of helium. It thus loses a definite portion of its mass and of its energy. Helium, which is chemically one of the most inert of the elements, is, when possessed of such great kinetic energy, able to penetrate and ionize the atoms which it meets in its path. It spends its energy in the act of ionizing them, coming to rest, when it moves in air, in a few centimeters. Its particular initial velocity depends upon which of the radioactive elements has given rise to it. The length of its path is therefore different according to the radioactive element from which it proceeds. The retardation which it experiences in its path depends entirely upon the atomic weight of the atoms which it traverses. As it advances in its path its effectiveness in ionizing the atom rapidly increases and attains a very marked maximum. In a gas the ions produced being much crowded together recombine rapidly; so rapidly that the actual ionization may be quite concealed unless a sufficiently strong electric force is applied to separate them. Such is a brief summary of the climax of radioactive discovery—the birth, life, and death of the alpha ray. Its advent into science has altered fundamentally our conception of matter. It is fraught with momentous bearings upon geological science. How the work of the alpha ray is sometimes recorded visibly in the rocks and what we may learn from that record I propose now to bring before you.

In certain minerals, notably the brown variety of mica known as biotite, the microscope reveals minute circular marks occurring here and there, quite irregularly. The most usual appearance is that of a circular area darker in color than the surrounding mineral. The radii of these little disk-shaped marks when well defined are found

to be remarkably uniform, in some cases four-hundredths of a millimeter and in others three-hundredths, about. These are the measurements in biotite. In other minerals the measurements are not quite the same as in biotite. Such minute objects are quite invisible to the naked eye. In some rocks they are very abundant, indeed they may be crowded together in such numbers as to darken the color of the mineral containing them. They have long been a mystery to petrologists.

Close examination shows that there is always a small speck of a foreign body at the center of the circle, and it is often possible to identify the nature of this central substance, small though it be. Most generally it is found to be the mineral zircon. Now, this mineral was shown by Strutt to contain radium in quantities much exceeding those found in ordinary rock substances. Some other mineral may occasionally form the nucleus, but we never find any which is not known to be specially likely to contain a radioactive substance. Another circumstance we notice. The smaller this central nucleus the more perfect in form is the darkened circular area surrounding it. When the circle is very perfect and the central mineral clearly defined at its center we find by measurement that the radius of the darkened area is generally 0.033 millimeter. It may sometimes be 0.040 millimeter. These are always the measurements in biotite. In other minerals the radii are a little different.

We see in the photograph (pl. 1, fig. 1), much magnified, a halo contained in biotite. We are looking at a region in a rock section, the rock being ground down to such a thickness that light freely passes through it. The biotite is in the center of the field. Quartz and feldspar surround it. The rock is a granite. The biotite is not all one crystal. Two crystals, mutually inclined, are cut across. The halo extends across both crystals, but owing to the fact that polarized light is used in taking the photograph it appears darker in one crystal than in the other. We see the zircon which composes the nucleus. The fine lineated appearance of the biotite is due to the cleavage of that mineral, which is cut across in the section.

The question arises whether the darkened area surrounding the zircon may not be due to the influence of the radioactive substances contained in the zircon. The extraordinary uniformity of the radial measurements of perfectly formed haloes (to use the name by which they have long been known) suggests that they may be the result of alpha radiation. For in that case, as we have seen, we can at once account for the definite radius as simply representing the range of the ray in biotite. The farthest-reaching ray will define the radius of the halo. In the case of the uranium family this will be radium C, and in the case of thorium it will be thorium C. Now

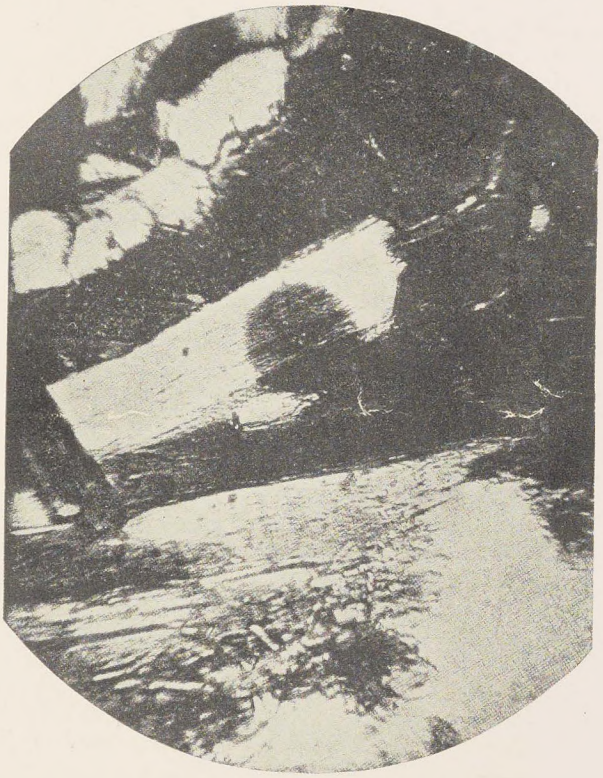


FIG. 1.



FIG. 2.

PLEOCHROIC HALOES.

here we possess a means of at once confirming or rejecting the view that the halo is a radioactive phenomenon and occasioned by alpha radiation; for we can calculate what the range of these rays will be in biotite, availing ourselves of Bragg's additive law, already referred to. When we make this calculation we find that radium C just penetrates 0.033 millimeter and thorium C 0.040 millimeter. The proof is complete that we are dealing with the effects of alpha rays. Observe now that not only is the coincidence of measurement and calculation a proof of the view that alpha radiation has occasioned the halo, but it is a very complete verification of the important fact stated by Bragg, that the stopping power depends solely on the atomic weight of the atoms traversed by the ray.

We have seen that our examination of the rocks reveals only the two sorts of halo, the radium halo and the thorium halo. This is not without teaching. For why not find an actinium halo? Now, Rutherford long ago suggested that this element and its derivatives were probably an offspring of the uranium family; a side branch, as it were, in the formation of which relatively few transforming atoms took part. On Rutherford's theory, then, actinium should always accompany uranium and radium, but in very subordinate amount. The absence of actinium haloes clearly supports this view. For if actinium was an independent element we would be sure to find actinium haloes. The difference in radius should be noticeable. If, on the other hand, actinium was always associated with uranium and radium, then its effects would be submerged in those of the much more potent effects of the uranium series of elements.

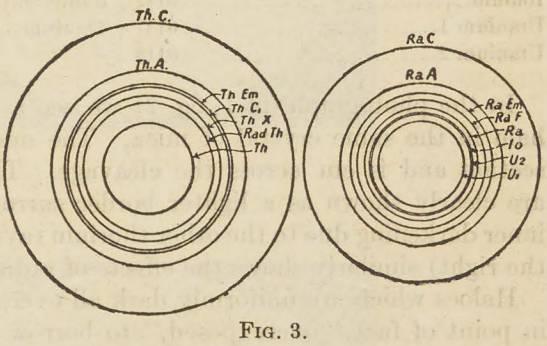


FIG. 3.

It will have occurred to you already that if the radioactive origin of the halo is assured the shape of a halo is not really circular, but spherical. This is so. There is no such thing as a disk-shaped halo. The halo is a spherical volume containing the radioactive nucleus at its center. The true radius of the halo may, therefore, only be measured on sections passing through the nucleus.

In order to understand the mode of formation of a halo we may profitably study on a diagram the events which go on within the halo sphere. Such a diagram is seen in figure 3. It shows to relatively correct scale the limiting range of all the alpha-ray producing

members of the uranium and thorium families. We know that each member of a family will exist in equilibrium amount within the nucleus possessing the parent element. Each alpha ray leaving the nucleus will just attain its range and then cease to affect the mica. Within the halo sphere there must be, therefore, the accumulated effects of the influences of all the rays. Each has its own sphere of influence, and the spheres are all concentric.

The radii in biotite of the several spheres are given in the following table:

URANIUM FAMILY.	Millimeter.	THORIUM FAMILY.	Millimeter.
Radium C	0.0330	Thorium C_2	0.040
Radium A	.0224	Thorium A	.026
Ra emanation	.0196	Th emanation	.023
Radium F	.0177	Thorium C_1	.022
Radium	.0156	Thorium X	.020
Ionium	.0141	Radiothorium	.019
Uranium 1	.0137	Thorium	.013
Uranium 2	.0118		

In the photograph (pl 1, fig. 2) we see a uranium and a thorium halo in the same crystal of mica. The mica is contained in a rock section and is cut across the cleavage. The effects of thorium C_2 are clearly shown as a lighter border surrounding the accumulated inner darkening due to the other thorium rays. The uranium halo (to the right) similarly shows the effects of radium C, but less distinctly.

Haloes which are uniformly dark all over, as described above, are, in point of fact, "overexposed," to borrow a familiar photographic term. Haloes are found which show much very beautiful internal detail. Too vigorous action obscures this detail just as detail is lost in an overexposed photograph. We may again have "underexposed" haloes in which the action of the several rays is incomplete or in which the action of certain of the rays has left little if any trace. Beginning at the most underexposed haloes we find circular dark marks having the radius 0.012 or 0.013 millimeter. These haloes are due to uranium, although their inner darkening is doubtless aided by the passage of rays which were too few to extend the darkening beyond the vigorous effects of the two uranium rays. Then we find haloes carried out to the radii 0.016, 0.018, and 0.019 millimeter. The last sometimes show very beautiful outer rings having radial dimensions such as would be produced by radium A and radium C. Finally we may have haloes in which interior detail is lost so far out as the radius due to emanation or radium A, while outside this floats the ring due to radium C. Certain variations of these effects may occur, marking, apparently, different stages of exposure. Plate 2 illustrates some of these stages, figure 2 of this plate being greatly enlarged to show clearly the halo sphere of radium A.

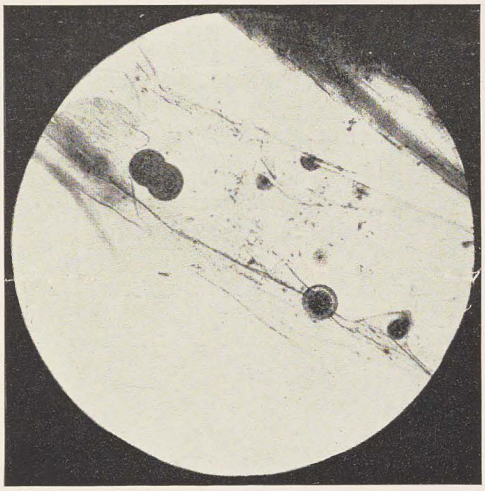


FIG. 1.

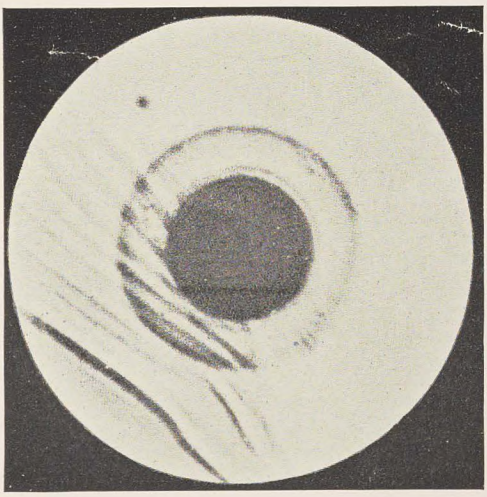


FIG. 2.

PLEOCHROIC HALOES.

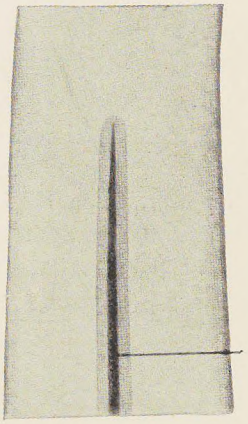


FIG. 1.



FIG. 2.

PLEOCHROIC HALOES.

In most of the cases referred to above the structure evidently shows the existence of concentric spherical shells of darkened biotite. This is a very interesting fact, for it proves that in the mineral the alpha ray gives rise to the same increased ionization toward the end of its range as Bragg determined in the case of gases; and we must conclude that the halo in every case grows in this manner. A spherical shell of darkened biotite is first produced, and the inner coloration is only effected as the more feeble ionization along the track of the ray in course of ages gives rise to sufficient alteration of the mineral. This more feeble ionization is, near the nucleus, enhanced in its effects by the fact that there all the rays combine to increase the ionization, and, moreover, the several tracks are there crowded by the convergency to the center. Hence the most elementary haloes seldom show definite rings due to uranium, etc., but appear as embryonic disk-like markings. The photographs on the screen[1] illustrate many of the phases of halo development. Rutherford succeeded in making a halo artificially by compressing into a capillary glass tube a quantity of the emanation of radium. As the emanation decayed the various derived products came into existence and all the several alpha rays penetrated the glass, darkening the walls of the capillary out to the limit of the range of radium C in glass. Figure 1 on plate 3 is a magnified view of the tube. The dark central part is the capillary. The tubular halo surrounds it. This experiment has, however, been anticipated by some scores of millions of years, for here is the same effect in a biotite crystal (pl. 3, fig. 2). Along what are apparently tubular passages or cracks in the mica a solution rich in radioactive substances has moved, probably during the final consolidation of the granite in which the mica occurs. A continuous and very regular halo has developed along these conduits. A string of halo spheres may lie along such passages. We must infer that solutions or gases able to establish the radioactive nuclei moved along these conduits, and we are entitled to ask if all the haloes in this biotite are not, in this sense, of secondary origin. There is, I may add, much to support such a conclusion.

It must not be thought that the underexposed halo is a recent creation. By no means. All are old, appallingly old; and in the same rock all are probably of the same, or nearly the same, age. The underexposure is simply due to a lesser quantity of the radioactive elements in the nucleus. They are underexposed, in short, not because of lesser duration of exposure, but because of insufficient action, as when in taking a photograph the stop is not open enough for the time of the exposure.

The halo has so far told us that the additive law is obeyed in solid media and that the increased ionization attending the slowing down

[1] Shown by lecturer but not here reproduced.

of the ray obtaining in gases also obtains in solids, for otherwise the halo would not commence its development as a spherical shell or envelope. But here we learn that there is probably a certain difference in the course of events attending the immediate passage of the ray in the gas and in the solid. In the former initial recombination may obscure the intense ionization near the end of the range. We can only detect the true end effects by artificially separating the ions by a strong electric force. If this recombination happened in the mineral we should not have the concentric spheres so well defined as we see them to be. What, then, hinders the initial recombination in the solid? The answer probably is that the newly formed ion is instantly used up in a fresh chemical combination. Nor is it free to change its place, as in the gas. There is simply a new equilibrium brought about by its sudden production. In this manner the conditions in the complex molecule of biotite, tourmaline, etc., may be quite as effective in preventing initial recombination as the most effective electric force we could apply. The final result is that we find the Bragg curve reproduced most accurately in the delicate shading of the rings making up the perfectly exposed halo.

That the shading of the rings reproduces the form of the Bragg curve projected, as it were, upon the line of advance of the ray and reproduced in depth of shading, shows that in yet another particular the alpha ray behaves much the same in the solid as in the gas. A careful examination of the outer edge of the circles always reveals a steep but not abrupt cessation of the action of the ray. Now, Geiger has investigated and proved the existence of scattering of the alpha ray by solids. We may therefore suppose, with much probability, that there is the same scattering within the mineral near the end of the range. The heavy iron atom of the biotite is, doubtless, chiefly responsible for this in biotite haloes. I may observe that this shading of the outer bounding surface of the sphere of action is found however minute the central nucleus. In the case of a nucleus of considerable size another effect comes in which tends to produce an enhanced shading. This will result if rays proceed from different depths in the nucleus. If the nucleus was of the same density and atomic weight as the surrounding mica there would be little effect. But its density and molecular weight are generally greater, hence the retardation is greater, and rays proceeding from deep in the nucleus experience more retardation than those which proceed from points near to the surface. The distances reached by the rays in the mica will vary accordingly, and so there will be a gradual cessation of the effects of the rays.

The result of our study of the halo may be summed up in the statement that in nearly every particular we have the phenomena which have been measured and observed in the gas reproduced on a minute

scale in the halo. Initial recombination seems, however, to be absent or diminished in effectiveness; probably because of the new stability instantly assumed by the ionized atoms.

One of the most interesting points about the halo remains to be referred to. The halo is always uniformly darkened all round its circumference and is perfectly spherical. Sections, whether taken in the plane of cleavage of the mica or across it, show the same exactly circular form, and the same radius. Of course, if there was any appreciable increase of range along or across the cleavage the form of the halo on the section across the cleavage should be elliptical. The fact that there is no measurable ellipticity is, I think, one which would not on first consideration be expected.

For what are the conditions attending the passage of the ray in a medium such as mica? According to crystallographic conceptions we have here an orderly arrangement of molecules, the units composing the crystal being alike in mass, geometrically spaced, and polarized as regards the attractions they exert one upon another. Mica, more especially, has the cleavage phenomenon developed to a degree which transcends its development in any other known substance. We can cleave it and again cleave it till its flakes float in the air, and we may yet go on cleaving it by special means till the flakes no longer reflect visible light. And not less remarkable is the uniplanar nature of its cleavage. There is little cleavage in any plane but the one, although it is easy to show that the molecules in the plane of the flake are in orderly arrangement and are more easily parted in some directions than in others. In such a medium beyond all others we must look with surprise upon the perfect sphere struck out by the alpha rays, because it seems certain that the cleavage is due to lesser attraction, and, probably, further spacing of the molecules, in a direction perpendicular to the cleavage.

It may turn out that the spacing of the molecules will influence but little the average number per unit distance encountered by rays moving in divergent paths. If this is so we seem left to conclude that in spite of its unequal and polarized attractions there is equal retardation and equal ionization in the molecule in whatever direction it is approached. Or, again, if the encounters indeed differ in number, then some compensating effect must exist whereby a direction of lesser linear density involves greater stopping power in the molecule encountered, and vice versa.

The nature of the change produced by the alpha rays is unknown. But the formation of the halo is not, at least in its earlier stages, attended by destruction of the crystallographic and optical properties of the medium. The optical properties are unaltered in nature but increased in intensity. This applies till the halo has become so darkened that light is no longer transmitted under the condi-

tions of thickness obtaining in rock sections. It is well known that there is in biotite a maximum absorption of a plane polarized light ray when the plane of vibration coincides with the plane of cleavage. A section across the cleavage then shows a maximum amount of absorption. A halo seen on this section simply produces this effect in a more intense degree. This is well shown in figure 1 (plate 1) on a portion of the halo sphere. The descriptive name "pleochroic halo" has originated from this fact. We must conclude that the effect of the ionization due to the alpha ray has not been to alter fundamentally the conditions which give rise to the optical properties of the medium. The increased absorption is probably associated with some change in the chemical state of the iron present. Haloes are, I believe, not found in minerals from which this element is absent. One thing is quite certain. The coloration is not due to an accumulation of helium atoms, i. e., of spent alpha rays. The evidence for this is conclusive. If helium was responsible we should have haloes produced in all sorts of colorless minerals. Now we sometimes see zircons in feldspars and in quartz, etc., but in no such case is a halo produced. And halo spheres formed within and sufficiently close to the edge of a crystal of mica are abruptly truncated by neighboring areas of feldspar or quartz, although we know that the rays must pass freely across the boundary. Again it is easy to show that even in the oldest haloes the quantity of helium involved is so small that one might say the halo sphere was a tolerably good vacuum as regards helium. There is, finally, no reason to suppose that the imprisoned helium would exhibit such a coloration, or, indeed, any at all.

I have already referred to the great age of the halo. Haloes are not found in the younger igneous rocks. It is probable that a halo less than a million years old has never been seen. This, prima facie, indicates an extremely slow rate of formation. And our calculations quite support the conclusions that the growth of a halo, if this has been uniform, proceeds at a rate of almost unimaginable slowness.

Let us calculate the number of alpha rays which may have gone to form a halo in the Devonian granite of Leinster.

It is common to find haloes developed perfectly in this granite and having a nucleus of zircon less than 5×10^{-4} centimeter in diameter. The volume of zircon is 65×10^{-12} cubic centimeter and the mass 3×10^{-10} gram, and if there was in this zircon 10^{-8} gram radium per gram (a quantity about five times the greatest amount measured by Strutt), the mass of radium involved is 3×10^{-18} gram. From this and from the fact ascertained by Rutherford that the number of alpha rays expelled by a gram of radium in one second is 3.4×10^{10}, we find that three rays are shot from the nucleus in a year. If now, geological time since the Devonian is 50 millions of years,

then 150 millions of rays built up the halo. If geological time since the Devonian is 400 millions of years, then 1,200 millions of alpha rays are concerned in its genesis. The number of ions involved, of course, greatly exceeds these numbers. A single alpha ray fired from radium C will produce 2.37×10^5 ions in air.

But haloes may be found quite clearly defined and fairly dark out to the range of the emanation ray and derived from much lesser quantities of radioactive materials. Thus a zircon nucleus with a diameter of but 3.4×10^{-4} centimeter formed a halo strongly darkened within, and showing radium A and radium C as clear smoky rings. Such a nucleus, on the assumption made above as to its radium content, expels one ray in a year. But, again, haloes are observed with less blackened pupils and with faint ring due to radium C, formed round nuclei of rather less than 2×10^{-4} centimeter diameter. Such nuclei would expel one ray in five years. And even lesser nuclei will generate in these old rocks haloes with their earlier characteristic features clearly developed. In the case of the most minute nuclei, if my assumption as to the uranium content is correct, an alpha ray is expelled, probably, no oftener than once in a century, and possibly at still longer intervals.

The equilibrium amount of radium contained in some nuclei may amount to only a few atoms. Even in the case of the larger nuclei and more perfectly developed haloes the quantity of radium involved is many millions of times less than the least amount we can recognize by any other means. But the delicacy of the observation is not adequately set forth in this statement. We can not only tell the nature of the radioactive family with which we are dealing, but we can recognize the presence of some of its constituent members. I may say that it is not probable the zircons are richer in radium than I have assumed. My assumption involves about 3 per cent of uranium. I know of no analyses ascribing so great an amount of uranium to zircon. The variety cyrtolite has been found to contain half this amount, about. But even if we doubled our estimate of radium content, the remarkable nature of our conclusions is hardly lessened.

It may appear strange that the ever-interesting question of the earth's age should find elucidation from the study of haloes. Nevertheless the subjects are closely connected. The circumstances are as follows: Geologists have estimated the age of the earth since denudation began, by measurements of the integral effects of denudation. These methods agree in showing an age of about 10^8 years. On the other hand, measurements have been made of the accumulation in minerals of radioactive débris—the helium and lead—and results obtained which, although they do not agree very well among themselves, are concordant in assigning a very much greater

age to the rocks. If the radioactive estimate is correct, then we are now living in a time when the denudative forces of the earth are about eight or nine times as active as they have been on the average over the past. Such a state of things is absolutely unaccountable. And all the more unaccountable because from all we know we would expect a somewhat lesser rate of solvent denudation as the world gets older and the land gets more and more loaded with the washed-out materials of the rocks.

Both the methods referred to of finding the age assume the principle of uniformity. The geologist contends for uniformity throughout the past physical history of the earth. The physicist claims the like for the change rates of the radioactive elements. Now the study of the rocks enables us to infer something as to the past history of our globe. Nothing is, on the other hand, known respecting the origin of uranium or thorium—the parent radioactive bodies. And while not questioning the law and regularity which undoubtedly prevail in the periods of the members of the radioactive families, it appears to me that it is allowable to ask if the change rate of uranium has been always what we now believe it to be. This comes to much the same thing as supposing that atoms possessing a faster change rate once were associated with it which were capable of yielding both helium and lead to the rocks. Such atoms might have been collateral in origin with uranium from some antecedent element. Like helium, lead may be a derivative from more than one sequence of radioactive changes. In the present state of our knowledge the possibilities are many. The change rate is known to be connected with the range of the alpha ray expelled by the transforming element; and the conformity of the halo with our existing knowledge of the ranges is reason for assuming that, whatever the origin of the more active associate of uranium, this passed through similar elemental changes in the progress of its disintegration. There may, however, have been differences in the ranges which the halo would not reveal. It is remarkable that uranium at the present time is apparently responsible for two alpha rays of very different ranges. If these proceed from different elements, one should be faster in its change rate than the other. Some guidance may yet be forthcoming from the study of the more obscure problems of radioactivity.

Now, it is not improbable that the halo may contribute directly to this discussion. We can evidently attack the biotite with a known number of alpha rays and determine how many are required to produce a certain intensity of darkening, corresponding to that of a halo with a nucleus of measurable dimensions. On certain assumptions, which are correct within defined limits, we can calculate, as I have done above, the number of rays concerned in forming the

halo. In doing so we assume some value for the age of the halo. Let us take the maximum radioactive value. A halo originating in Devonian times may attain a certain central blackening from the effects of, say, 10^8 rays. But now suppose we find that we can not produce the same degree of blackening with this number of rays applied in the laboratory. What are we to conclude? I think there is only the one conclusion open to us, that some other source of alpha rays, or a faster rate of supply, existed in the past. And this conclusion would explain the absence of haloes from the younger rocks; which, in view of the vast range of effects possible in the development of haloes, is, otherwise, not easy to account for. It is apparent that the experiment on the biotite has a direct bearing on the validity of the radioactive method of estimating the age of the rocks. It is now being carried out by Prof. Rutherford under reliable conditions.

Finally, there is one very certain and valuable fact to be learned from the halo. The halo has established the extreme rarity of radioactivity as an atomic phenomenon. One and all of the speculations as to the slow breakdown of the commoner elements may be dismissed. The halo shows that the mica of the rocks is radioactively sensitive. The fundamental criterion of radioactive change is the expulsion of the alpha ray. The molecular system of the mica and of many other minerals is unstable in presence of these rays, just as a photographic plate is unstable in presence of light. Moreover, the mineral integrates the radioactive effects in the same way as a photographic salt integrates the effects of light. In both cases the feeblest activities become ultimately apparent to our inspection. We have seen that one ray in each year since the Devonian period will build the fully formed halo, unlike any other appearance in the rocks. And we have been able to allocate all the haloes so far investigated to one or the other of the known radioactive families. We are evidently justified in the belief that had other elements been radioactive we must either find characteristic haloes produced by them, or else find a complete darkening of the mica. The feeblest alpha rays emitted by the relatively enormous quantities of the prevailing elements, acting over the whole duration of geological time—and it must be remembered that the haloes we have been studying are comparatively young—must have registered their effects on the sensitive minerals. And thus we are safe in concluding that the common elements, and, indeed, many which would be called rare, are possessed of a degree of stability which has preserved them unchanged since the beginning of geological time. Each unaffected flake of mica is, thus, unassailable proof of a fact which but for the halo would, probably, have been forever beyond our cognizance.

2.14
1.57
17

